Available online at www.sciencedirect.com
SCIENCE DIRECT®
ELSEVIER
Ocean Engineering 30 (2003) 2239–2253
OCEAN ENGINEERING
www.elsevier.com/locate/oceaneng

Estimation of wind speed and wave height during cyclones

V. Sanil Kumar *, S. Mandal, K. Ashok Kumar

Ocean Engineering Division, National Institute of Oceanography, Goa - 403 004, India

Received 17 September 2002; accepted 8 January 2003

Abstract

Wave and wind characteristics based on the cyclones, in the vicinity of the Nagapattinam coastline (east coast of India) were estimated. In all, 11 cyclones have crossed near the study region during 1960–1996. For the four severe cyclones, the isobaric charts were collected at three hourly intervals from the India Meteorological Department. The storm variables such as central pressure, radius of maximum wind, speed of forward motion and direction of storm movement were extracted and the method based on standard Hydromet pressure profile, were used for the hindcast of storm wind fields. For all the cyclones the maximum significant wave height within the storm and its associated spectral peak period was estimated using the Young's model considering the moving wind field and the results are compared with the hurricane wave prediction techniques provided in the shore protection manual published by the US Army Corps of Engineers in 1984. The study shows that the estimated wind speed and the data reported by ships were comparable. Empirical expressions relating wind speed, wave height and wave period to storm parameters were derived. The design wave height for different return periods was obtained by fitting a two-parameter Weibull distribution to the estimated significant wave heights. The design wave height was 9.39 m for 1 in 100 year return period for a direct hit of cyclone.

Keywords: Storm wind fields; Young's model; Design wave height; Spectral peak period; Ocean waves

* Corresponding author. Tel.: 0091-832-2456700 ext. 4327; fax: 0091-832-2456702.
E-mail address: sanil@darya.nio.org (V.S. Kumar).

0029-8018/$ - see front matter © 2003 Elsevier Ltd. All rights reserved.
doi:10.1016/S0029-8018(03)00076-3

1. Introduction

Estimation of extreme wave height during a cyclone/storm has considerable importance in planning and operation of offshore activities and design of offshore platforms. Various wave prediction models were developed and presented by many scholars based on different approaches. SWAMP (1985) gives a comparison of various wave prediction models and also the merits and demerits of each model. The complicated wave generating processes within cyclones make estimation of the wave conditions associated with a given storm difficult. A more realistic estimation of wave height during cyclone can be done using the Young's model, which considers the moving wind field (Young, 1988). The Young's model was developed based on the concept of the equivalent fetch and the standard JONSWAP fetch-limited growth relationships (Hasselmann et al., 1973).

The Nagapattinam coastline consists of long, narrow and low sandy beaches. The nearshore bathymetry is relatively steep, straight and parallel to the coast. The tides in this region are semi diurnal with an average spring range of 0.67 m and neap range of 0.19 m. Extreme wave conditions occur along this coast during severe tropical cyclones which are frequent in the Bay of Bengal during the northeast monsoon (October to January). Kumar et al. (1999) studied the wave characteristics along this coast based on the measured data during November and December 1995. Wave statistics around the Indian coast based on ship reported deep water wave data was carried out by Chandramohan et al. (1991). Since the wave measurement period of 1995 there has been no occurrence of the cyclone and the data was measured at a shallow location having a water depth of 15 m, a study was conducted to find the wave characteristics at deep water during the passage of the cyclone. The objective of the present study is to estimate the wind and wave characteristics based on the cyclones, which cross in the vicinity of the Nagapattinam coastline.

2. Methods

2.1. Estimation of wind speed

The storm variables viz. (i) central pressure (P_0), (ii) radius of maximum wind (R), (iii) speed of forward motion (V_{fm}), (iv) direction of storm movement, (v) latitude and (vi) longitude for the cyclones were extracted using the isobaric charts from the archives of the India Meteorological Department (IMD) at 3 hourly time intervals. The method based on standard Hydromet pressure profile presented by Varkey (1985) and Varkey et al. (1996) was used for the hindcast of storm wind fields.

The following equation proposed for the cyclonic storms in Indian seas by Natarajan and Ramamurthy (1995) was also examined.

$$V_m = 7\sqrt{P_n - P_o} \quad (1)$$

where V_m is the maximum wind speed in m/s, P_o and P_n are the central and peripheral

pressures in mb of the cyclone. The peripheral pressure was taken as 1012 mb based on the study considering many past storms in the Bay of Bengal carried out by Varkey (1985).

Shea and Gray (1973) studied a large number of hurricanes and give a relationship between maximum wind and central pressure. According to their study, a central pressure of 965 mb will give a maximum wind speed between 27 and 49 m/s and their best fit curve gives a maximum wind speed of 37 m/s whereas Eq. (1) gave a value of 33 m/s.

According to USACE (1984), the maximum wind speed (U_R) for a moving hurricane is as below.

$$U_R = 0.865\, U_{max} + 0.5 V_{fm} \quad (2)$$

where $U_{max} = 0.447\ [14.5\ (P_n - P_0)^{1/2} - R\ (0.31\ f)]$
f=coriolis parameter
R=radius of maximum wind speed.

2.2. Historical data on cyclones that occur in the study region

The following cyclones passed close to the study region were considered in the present study. The tracks of these cyclones are shown in Fig. 1. The times referred are the Greenwich Mean Time (GMT).

1. 20–23 December 1964
2. 31 December 1965–3 January 1966

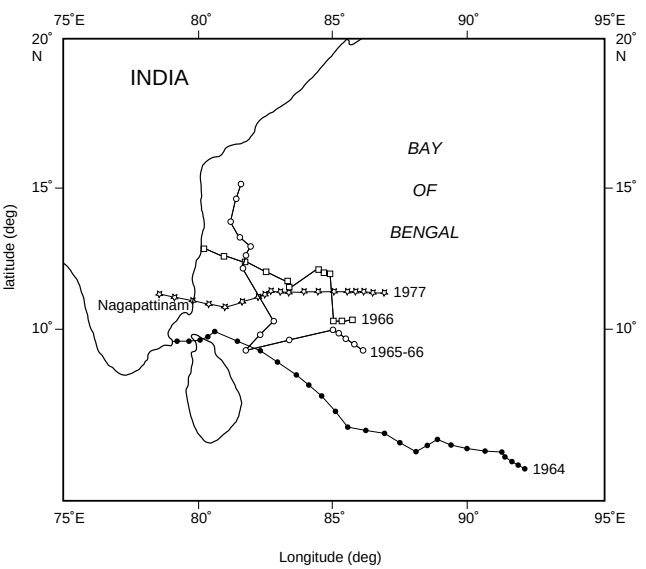

Fig. 1. Tracks of cyclones that crossed near study region.

3. 29 April–1 May 1966
4. 8–12 November 1977.

Other cyclones reported in 1979, 1981, 1984, 1987, 1991 and 1993 were also considered in the estimation of wave heights.

2.3. Estimation of waves

Young's model (Young, 1988) was used in the estimation of wave characteristics for the cyclones considered. The input parameters to the model were the radius of maximum wind for the storm, R, together with the maximum wind speed, V_{max}, and the speed of forward motion, V_{fm} and it estimates the maximum significant wave height (H_s) and peak spectral period (T_p) within the storm. Using the JONSWAP fetch-limited growth relationship, the significant wave height and the spectral peak period of the maximum waves in the storm are estimated as given below.

$$\frac{g\,H_s}{V_{max}^2} = 0.0016\left(\frac{gF}{V_{max}^2}\right)^{0.5} \tag{3}$$

$$\frac{g\,T_p}{2\pi\,V_{max}} = 0.045\left(\frac{gF}{V_{max}^2}\right)^{0.33} \tag{4}$$

where g is the acceleration of gravity and F is the fetch length which is estimated from the speed of forward motion and radius of maximum wind (Young, 1988).

According to USACE (1984) for a slow moving hurricane, the following equations may be used to obtain the deep-water significant wave height (H_s) and period (T_s) at the point of maximum wind.

$$H_s = 5.03\; e^{\frac{R\Delta P}{4700}}\left(1 + \frac{0.29\,\alpha\,V_{fm}}{\sqrt{U_R}}\right) \tag{5}$$

$$T_s = 8.6\; e^{\frac{R\Delta P}{9400}}\left(1 + \frac{0.145\,\alpha\,V_{fm}}{\sqrt{U_R}}\right) \tag{6}$$

where $\Delta P = P_n - P_0$.

3. Results and discussions

3.1. Wind speed

20–23 December 1964: The storm variables and the estimated maximum wind speed are presented in Fig. 2. The maximum wind speed computed was 27.2 m/s on 22.12.1964 at 1430 hrs when the depression was at 08.6° N, 82.6° E. Figure shows that as the central pressure decreases the wind speed increases.

31 December 1965–3 January 1966: The low-pressure area formed on 31.12.1965

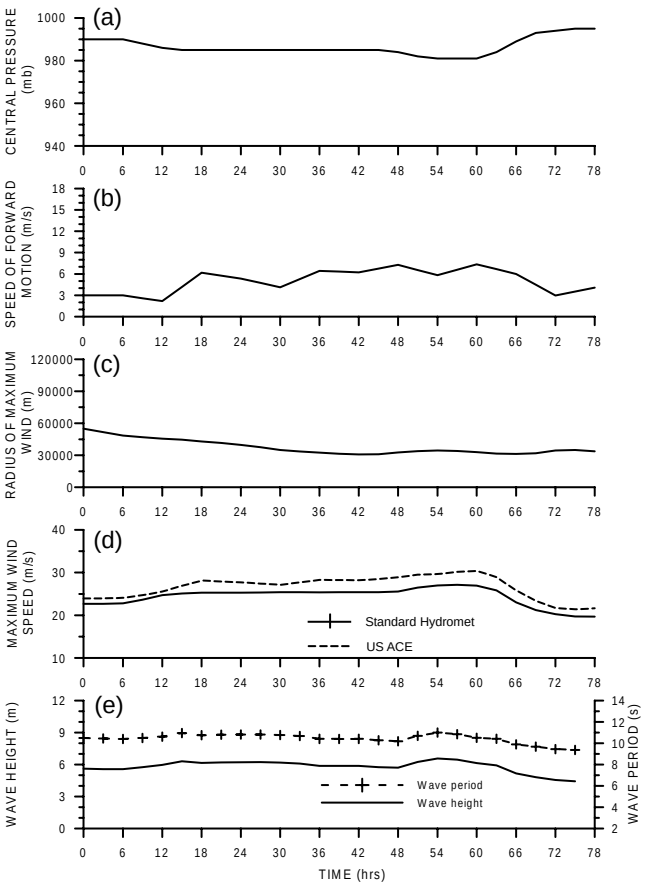

Fig. 2. Storm variables and wave parameters for December 1964 cyclone.

at 09° N, 85.5° E moved towards Bay of Bengal. Initially it moved in the westerly direction and then moved towards the north. The maximum wind speed during the above period was 25.4 m/s (Fig. 3) on 2.1.1966 at 1130 hrs when the cyclone was at 13.6° N, 81° E.

29 April–1 May 1966: The low pressure area formed on 29.4.1966 0530 hrs at 10° N, 85.2° E moved towards the Bay of Bengal. The storm variables and the estimated maximum wind speed are presented in Fig. 4. The radius of maximum wind was found to be more around 90 km. The maximum wind speed during the period was 23 m/s on 30.4.1966 0830 hrs when the cyclone was at 11.35° N, 83.5° E.

8–12 November 1977: Pant et al. (1980) have described the details of this cyclone. The low-pressure area formed in the south Andaman Sea concentrated into a depression on 8.11.1977 and intensified into a severe cyclonic storm on 11.11.1977. A ship about 300 km away from the storm center reported surface wind speed of 15 m/s on the 10th at 0600 hrs. On the 12th morning a ship about 150 km to the

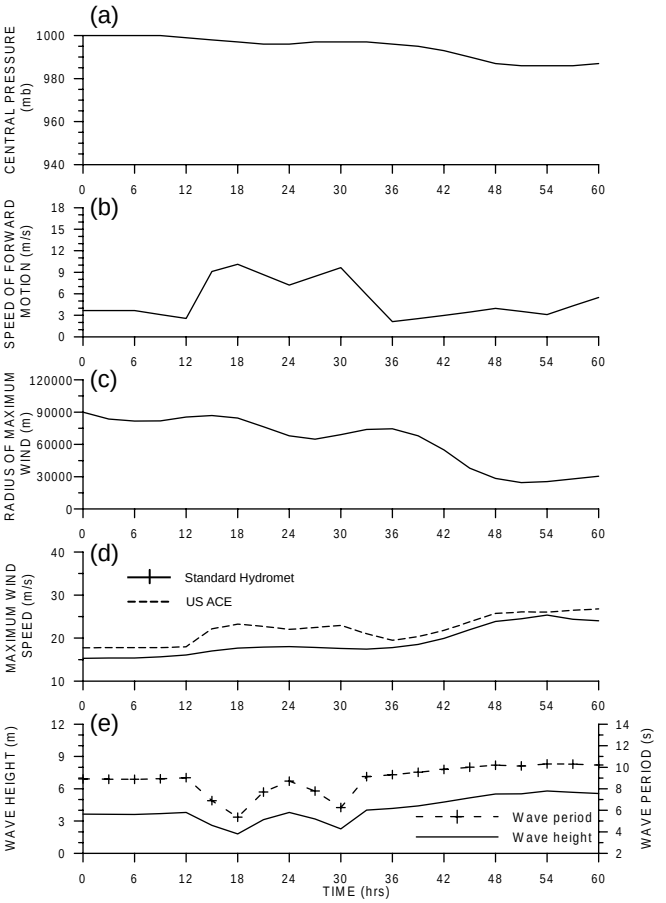

Fig. 3. Storm variables and wave parameters for December 1965–January 1966 cyclone.

east of the storm center reported wind speed of 13 to 15 m/s and the estimated wind speed is 12.5 m/s. Karaikal which is 25 km to the north of Nagapattinam recorded surface winds of about 23 m/s between 2200 and 2400 hrs of 11th and the lowest mean sea level pressure of 991 mb at about 2230 hrs of 11th and the estimated wind speed is 18 m/s. The storm variables and the estimated maximum wind speed are presented in Fig. 5. Estimated maximum wind speed was 28.3 m/s on 11.11.1977 at 1800 hrs. The distribution of wind speed for the maximum wind condition is estimated and presented in Fig. 6. The figure shows that the wind speed reduces to 12.5 m/s within 150 km distance from the centre of the storm.

The average value of radius of maximum wind for all of the four cyclones considered was 59 km. Hsu and Yan (1998) found that the mean value of R as 47 km, considering a total of 59 hurricanes with central pressure varying from 909 to 993 mb affecting the US coastline from 1893 to 1979. Since the real time value of R is

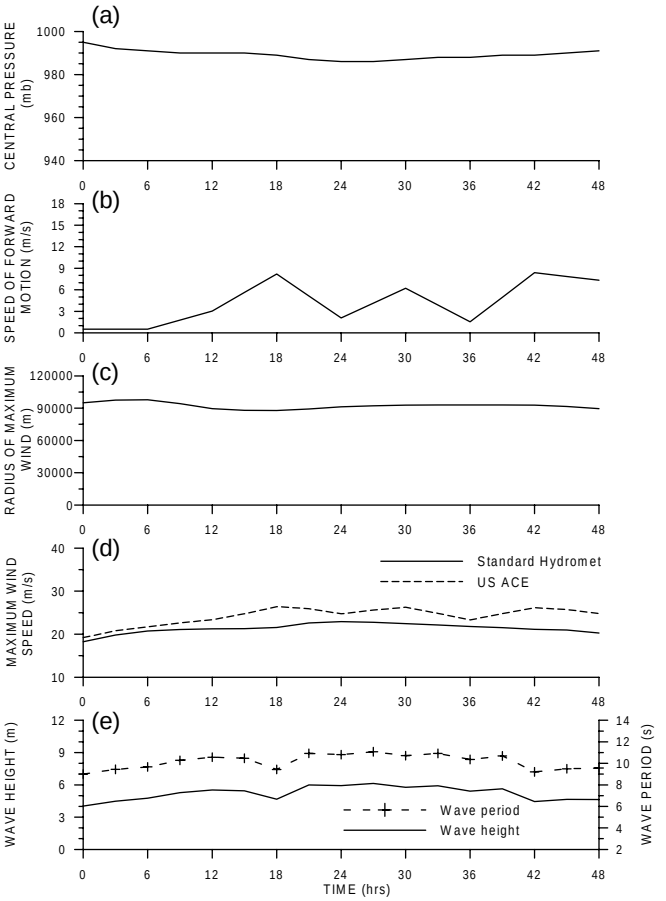

Fig. 4. Storm variables and wave parameters for April 1966 cyclone.

not always available for the cyclones along the Indian coast, a value of 59 km can be considered in the estimation of wind speed and wave height.

The wind speed computed following the method of USACE (Eq. (2)) is 1.1 times the corresponding values estimated using the standard hydromet profile. The comparison between wind speed estimated in the present study and the proposed Eq. (1) for the cyclonic storms in Indian seas by Natarajan and Ramamurthy (1995) shows that if the coefficient 7 is modified to 4.74 then a correlation coefficient of 0.9 is obtained between the two methods (Fig. 7).

The multiple regression analysis carried out resulted in the following empirical relation (Eq. (7)) which can be easily used to estimate the wind speed from the known values of central pressure, speed of forward motion and radius of maximum wind with a correlation coefficient of 0.81 (Fig. 8).

$$V_{\max} = 4.298\,(P_n - P_o)^{0.527}\, V_{fm}^{1.105E-3}\, R^{-2.153E-5}. \quad (7)$$

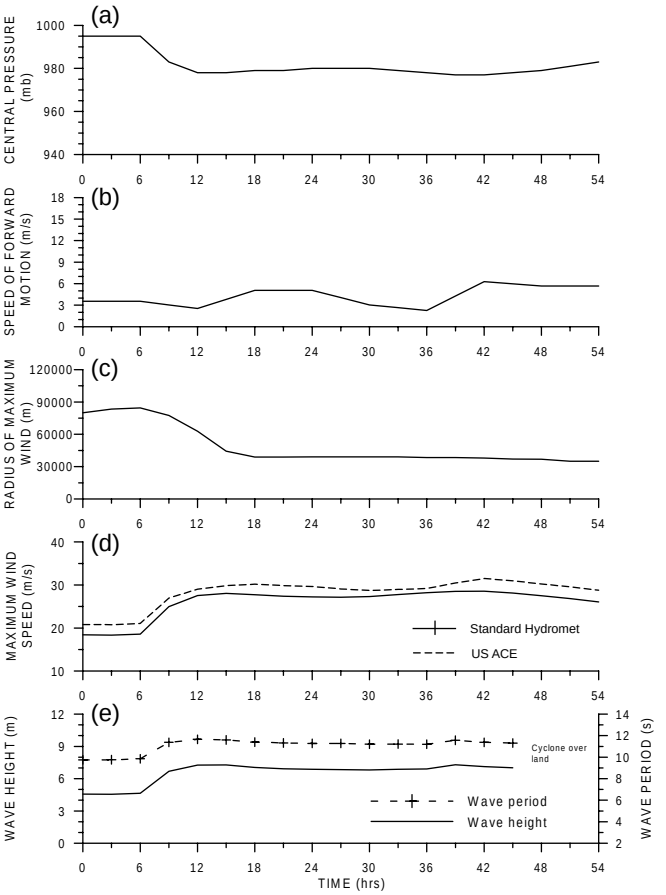

Fig. 5. Storm variables and wave parameters for November 1977 cyclone.

3.2. Wave height and period

The significant wave height and peak wave period estimated for different cyclones along with the input parameters are given in Table 1. The variation of significant wave height and peak wave period at three hourly intervals for the cyclones (a) to (d) are shown in Fig. 2e to 5e. The significant wave height estimated using the USACE method (Eq. (5)) is found to deviate from the value obtained using the Young's method (Eq. (3)) (Fig. 9). The reason for the deviation is due to the fact that USACE method is for a slow moving hurricane on the Atlantic and Pacific Ocean, whereas the average speed of the cyclone in the present case is 6 m/s. Similarly there is a deviation in the estimated value of the peak period using Eqs. (4) and (6) (Fig. 10).

Considering the cyclones crossed close to the study area it was found that a maximum wind speed of 28.3 m/s occurred in 1977 and 33.4 m/s in 1984. On analyz-

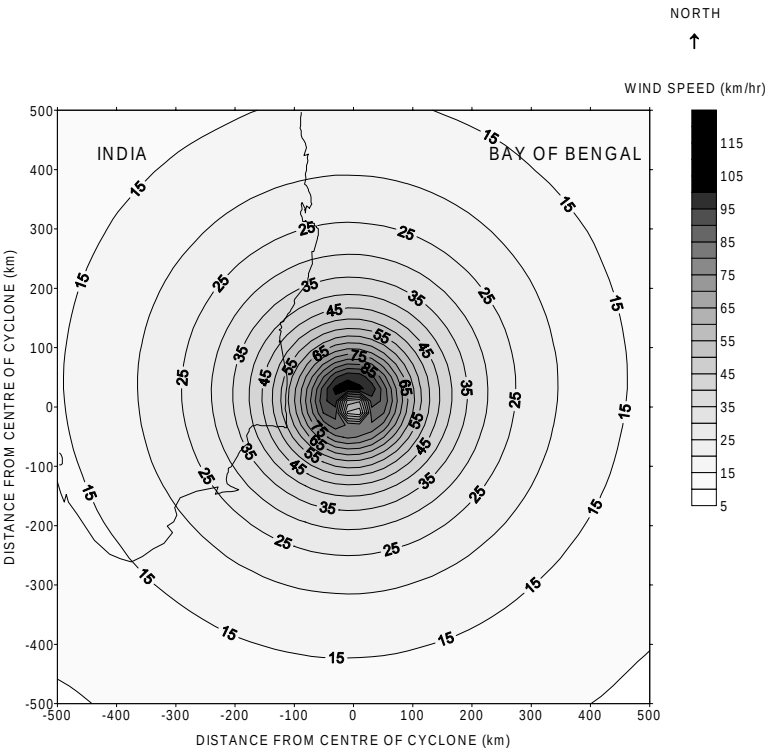

Fig. 6. Estimated wind speed on 11 November 1977 at 1800 hrs.

ing the cyclonic tracks it was found that the 1977 cyclone crossed the study region. During the passage of the cyclone a maximum wind speed of around 28 m/s for the duration of 33 hrs (from 10.11.1977 at 1200 hrs to 11.11.1977 at 2200 hrs) was present. For this maximum wind speed condition, the estimated significant wave height at deep water is 7.1 m and the peak wave period is 11.3 s.

For quicker estimates, a simple formula for Hs calculation as given below is proposed by Hsu et al. (2000). The H_s values estimated using the following Eq. (8) were found to be smaller than the values estimated using the Young's model (Fig. 9).

$$H_s = 0.2\,(P_n - P_o). \tag{8}$$

The following approximate formulae given in USACE (1984) for wave period is also examined with reference to the present data.

$$T_s = 12.1\,\sqrt{\frac{H_s}{g}}. \tag{9}$$

Hsu et al. (2000) found that the significant wave height and period estimated using Eqs. (8) and (9) were in good agreement with the measured values during Hurricane Georges in the Gulf of Mexico.

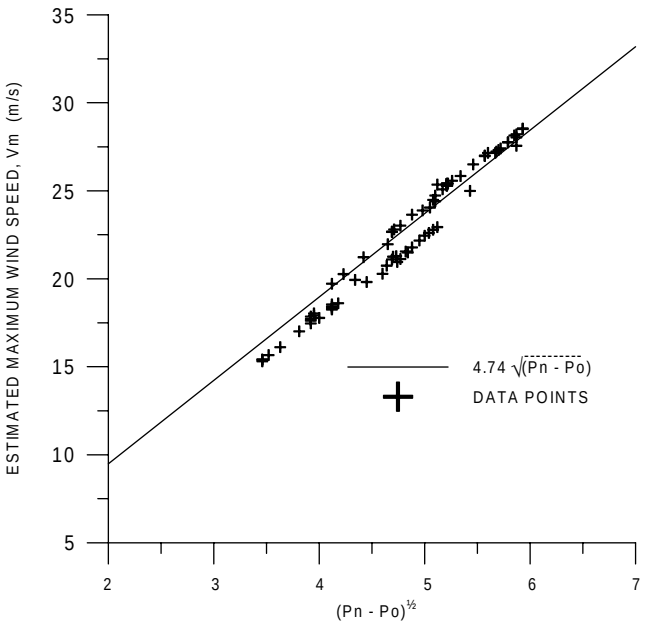

Fig. 7. Correlation between estimated maximum wind speed and square root of the difference in central pressure and peripheral pressure.

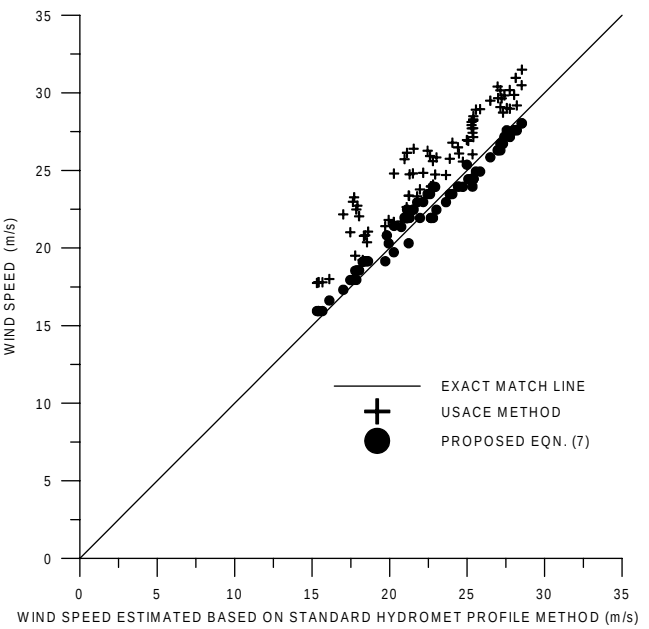

Fig. 8. Correlation between wind speed estimated based on different methods.

Table 1
Estimated significant wave height and peak wave period for maximum wind speed of different cyclones

Year of occurrence	Maximum wind speed estimated (m/s)	Speed of forward motion (m/s)	Radius of maximum wind (km)	Estimated fetch (km)	Estimated significant wave height (m)	Peak wave period (s)
1964	27.2	6.6	34.0	217	6.50	10.9
1965	25.4	3.1	25.5	200	5.80	10.3
1966	22.9	4.1	92.2	278	6.20	11.1
1977	28.3	6.3	38.0	237	7.05	11.3
1979	18.0	5.1	30.0	169	3.79	8.7
1981	12.9	5.4	30.0	131	2.38	7.1
1984	33.4	8.1	30.0	216	7.94	11.6
1987	15.4	2.6	30.0	155	3.10	8.0
1987	10.3	4.8	30.0	119	1.82	6.4
1991	20.6	3.0	30.0	187	4.54	9.4
1993	23.2	3.7	30.0	204	5.34	10.1

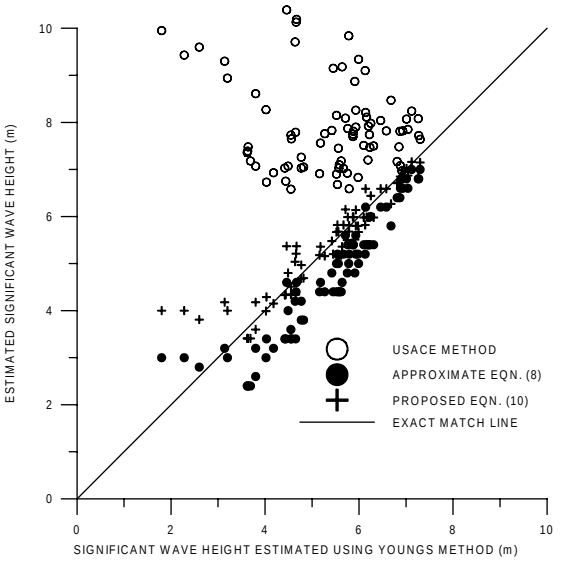

Fig. 9. Correlation between significant wave height estimated based on different methods.

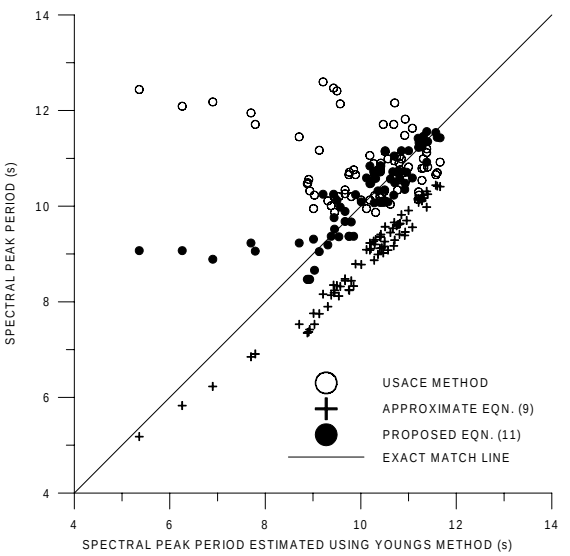

Fig. 10. Correlation between spectral peak period estimated based on different methods.

Based on multiple regression analysis, the following empirical expressions are derived to obtain the maximum significant wave height and spectral period from the known value of storm parameters such as central pressure, speed of forward motion and radius of maximum wind.

$$H_s = 0.61\,(P_n - P_o)^{0.69}\,V_{fm}^{5.43E\text{-}3}\,R^{1.43E\text{-}5} \quad (10)$$

$$T_S = 4.125\,(P_n - P_o)^{0.288}\,V_{fm}^{3.24E\text{-}3}\,R^{1.63E\text{-}5}. \quad (11)$$

A regression analysis was carried out between the wind speed and significant wave height and it was found that the following empirical relation holds good for the cyclones considered in the present study with a correlation coefficient of 0.9 (Fig. 11) when the wave height is more than 3 m. Kumar et al. (2001) found that the empirical relation (Eq. (12)) holds good for all 32 cyclones which occurred along the Indian coast from May 1961 to November 1982.

$$H_s = 0.25V_{max}. \quad (12)$$

Spectral peak period, T_p can also be estimated using the empirical relation given below from known value of significant wave height, H_s (Fig. 12).

$$T_p = 4.5H_s^{0.48}. \quad (13)$$

3.3. Design wave

Since the cyclones have not occurred at regular intervals, a Weibull distribution to the estimation of design wave height would not be realistic (Goda, 1999). However, design purposes, a 1:100 year wave height is required. Hence, the design wave heights for different return periods were estimated by fitting a two-parameter Weibull

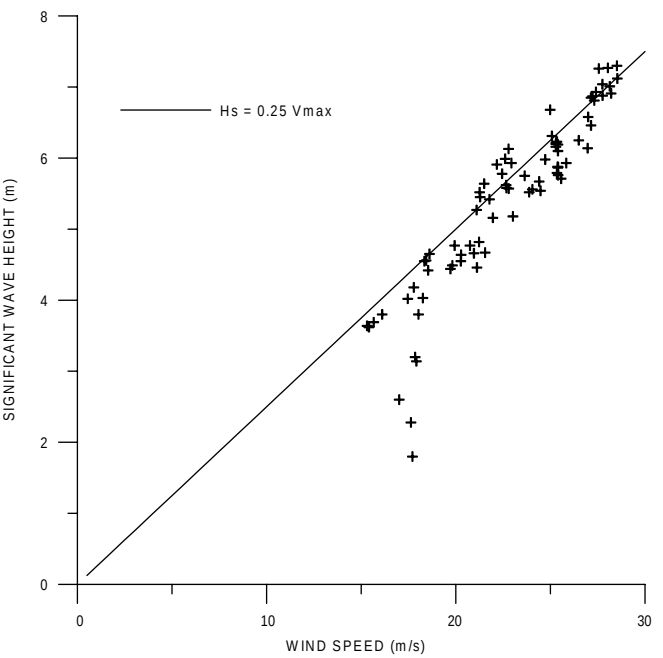

Fig. 11. Correlation between significant wave height and wind speed.

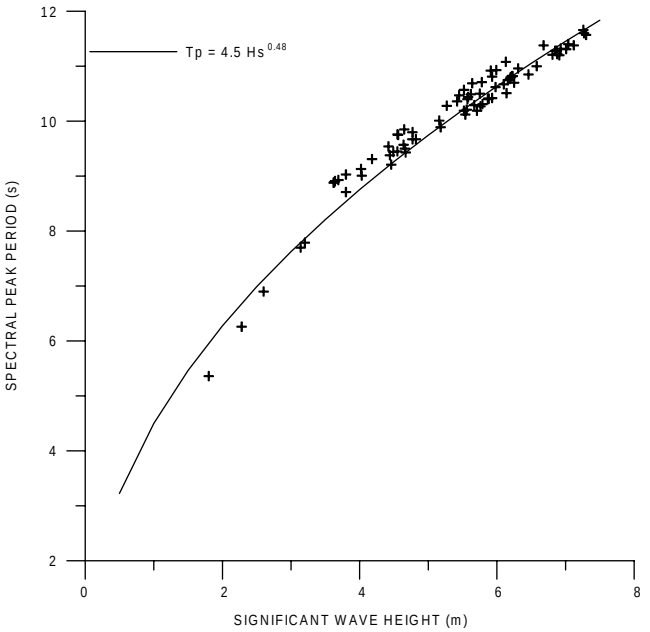

Fig. 12. Correlation between spectral peak period and significant wave height.

distribution to the estimated significant wave heights. In the estimation of design wave height it was considered that all the cyclones crossed close to the study region. The estimated design wave height is 9.39 m for 1 in 100 year return period for a direct hit of cyclone in the study region.

4. Conclusions

Even though the empirical Eqs. (7), (10) and (11) established based on the present study are dimensionally incorrect, they can be used for estimating wind speed, maximum significant wave height and the spectral peak period from the known values of storm variables. Since the real time value of R is not always available for the cyclones, a value of 59 km can be considered in the estimation of wind speed and wave height along the Indian coast. Peak wave period can be estimated using the empirical Eq. (13) from the known value of significant wave height. The maximum wind speed estimated during the cyclone is 33.4 m/s. For this maximum wind speed condition, the estimated wave height at deep water is 7.9 m with a peak wave period of 11.6 s. The design wave height is 9.39 m for 1 in 100 year return period for a direct hit of cyclone in the study region.

Acknowledgements

The authors thank Dr. M.J. Varkey, scientist for providing the software for estimation of wind field and they acknowledge the Director of the institute for permission to publish the paper. This paper is NIO contribution number 3809.

References

Chandramohan, P., Kumar, V.S., Nayak, B.U., 1991. Wave statistics around the Indian coast based on ship observed data. Indian Journal of Marine Sciences 20 (2), 87–92.

Goda, Y., 1999. Personal discussion, Dept. of Civil Engineering, Yokohama National University, Japan.

Hasselmann, K., Bernett, T.P., Bouws, E., Carlson, H., Cartwright, D.E., Enke, K., Ewing, J.A., Gineapp, H., Hasselmann, D.E., Kruseman, P., Meerburg, A., Muller, P., Olbers, D.J., Richer, K., Sell, W., Walden, H., 1973. Measurements of wind wave growth and swell decay during the Joint North Sea Wave Project, JONSWAP, Suppl Rep No. A8(12), Dutch. Hydrogr Z.

Hsu, S.A., Yan, Z., 1998. A note on the radius of maximum wind for hurricanes. Journal of Coastal Research 14, 667–668.

Hsu, S.A., Martin Jr, M.F., Blanchard, B.W., 2000. An evaluation of the USACE's deep water wave prediction techniques under hurricane conditions during Georges in 1998. Journal of Coastal Research 16 (3), 823–829.

Kumar, V.S., Deo, M.C., Anand, N.M., Chandramohan, P., 1999. Estimation of wave directional spreading in shallow water. Ocean Engineering 26, 83–98.

Kumar, V.S., Mandal, S., Manish, A. M. Rupali, S. P., 2001. Estimation of wind speeds and wave heights from tropical cyclones during 1961 to 1982, Technical Report, National Institute of Oceanography, NIO/TR-3/2001, 85 p.

Natarajan, R., Ramamurthy, K.M., 1995. Estimation of central pressure of cyclonic storms in the Indian seas. Indian Journal of Meteorology, Hydrology and Geophysics 26, 65–66.

Pant, P.S., Ramakrishnan, A.R., Jambunathan, R., 1980. Cyclones and depressions over the Indian seas in 1977. Mausam 31 (3), 337–356.

Shea, D.J., Gray, W.M., 1973. The hurricane's inner core region-I. Symmetric and asymmetric structure. Journal of Atmospheric Sciences 30, 1544–1564.

SWAMP Group, 1985. Ocean wave modelling. Plenum Press, New York, 256 p.

US Army Corps of Engineers, 1984. Shore protection manual. Vicksburg, Mississippi, pp. 3-81-3-84.

Varkey, M.J., 1985. A method for computation of surface wind fields of storms from surface isobars, Technical report, NIO/TR-2/85, National Institute of Oceanography, Goa, India.

Varkey, M.J., Vaithiyanathan, R., Santanam, K., 1996. Wind fields of storms from surface isobars for wave hindcasting, International Conference in Ocean Engineering, IIT Madras, India, pp. 502–506.

Young, I.R., 1988. Parametric hurricane wave prediction model. Journal of Waterways Port Coastal and Ocean Engineering 114 (5), 637–652.